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Analysis of H_2 storage needs for early market "man-portable" fuel cell applications

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ABSTRACT

Hydrogen fuel cells can potentially reduce greenhouse gas emissions and the dependence on finite fossil fuel resources. Improvements in the storage of hydrogen are needed for more widespread use of hydrogen fuel cells. To help better understand the hydrogen storage needs in the future, this study analyzes opportunities for the near-term deployment of H_2-fueled fuel cells in man-portable power devices and personal electronics. The analysis engaged end users, equipment manufacturers, and technical experts to determine not only the most feasible devices for near-term deployment of hydrogen fuel cells but also the meaningful and realistic requirements for hydrogen storage in these applications. It was found that military personnel power generators, consumer battery rechargers, and specialized laptop computers offer the most potential for the incorporation of fuel cell technology. However, large improvements must be made in energy storage densities for hydrogen fuel cells to compete with batteries or direct methanol fuel cells in order to make fuel cells attractive if an inexpensive and convenient hydrogen supply is not available.
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1. Introduction

Efforts to reduce greenhouse gas emissions and the dependence on finite fossil fuel resources have led to the research and development of a variety of alternative energy solutions. Of particular interest is the hydrogen fuel cell, which is a viable alternative to petroleum-based power generation and in some specific applications, has already found implementation. Challenges with hydrogen storage, including cost, reversibility, and the storage mass and volumetric densities, have inhibited widespread deployment of such fuel cell technologies. Each type of hydrogen storage brings its own challenges. High pressure (5000 psi) gaseous storage suffers from poor volumetric density. Cryogenic methods suffer from the difficulty in maintaining a cryogenic liquid (at $\cong$20 K) for long periods. Solid-state methods such as using metal hydrides (i.e., NaAlH4), chemical hydrides (i.e., ammonia borane), or adsorption materials (high surface area carbon materials) suffer from difficulty achieving total control of the solid-state processes of hydrogen release and rehydrogenation.

The U.S. Department of Energy (DOE) has recently expanded the scope of its hydrogen storage and fuel cell technology interests to include the applications of fuel cells for man-portable electronic systems and, as a result, needs to understand the hydrogen storage and fuel cell requirements for using fuel cells in this arena. The purpose of this study is to solicit and analyze feedback from end users, manufacturers, and technical experts in these markets and not only determine the most amenable near-term man-portable markets for hydrogen fuel cells, but also capture and formulate the energy storage needs in these specific man-portable applications.

Consumer electronics and man-portable power areas pertain to fuel cell systems primarily targeting small-scale use. Specifically, "man-portable" refers to devices capable of

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being carried, worn, or held in-hand by an individual. Such devices generally have power ratings less than 100 W, with certain systems tailored to military applications having ratings ≅300 W. Due to the size and portability constraints of these applications, the upper limit of fuel cell power explored in this study was practically limited to 500 W.

There have been prior studies on using fuel cells in man-portable devices. An excellent review by Agnolucci [1] points out the hurdles that fuel cells and their fuels need to overcome to realistically penetrate the consumer electronics market, and it reaches several of the same conclusions as this work. However, it does not give technology specifications nor go so far as to suggest requirements for hydrogen storage systems for these devices. Ramirez-Salgado and Dominguez-Aguilar [2] examine the Mexican market for portable "micro" fuel cells, which they defined as having a power of 50 W or less, integrated into the consumer electronics products of cell phones, personal digital assistants (PDAs), laptop computers, and other devices. Unfortunately, they also do not assess the hydrogen storage requirements nor explicitly consult with end users or manufacturers to determine the challenges that may be faced by hydrogen fuel cells in the markets they consider. A paper by the U.S. Army [3] describes the issues relevant for hydrogen and fuel cells to be used in their particularly demanding portable power applications, but by its nature, the study is limited in scope. Hellman and van den Hoed [4] review the considerations for fuel cell commercialization but do not specifically address any market, fuel cell, or fuel type. A review by Kamarudin et al. [5] examines direct methanol fuel cells (DMFC) for cell phones and laptop computers while Kundu et al. [6] reviews micro fuel cell technology, which they define as 5 W or less. However, both are focused solely on fuel cell technology improvements and challenges and do not focus on hydrogen storage. A recent paper by the U.S. DOE [7] describes the technical hurdles of materials-based hydrogen storage methods for early-market deployment but does not include the man-portable applications.

Given this prior work, there is a need to identify promising near-term man-portable markets based on real feedback from end users and manufacturers, to assess the current state of energy storage devices in these markets, and to suggest quantitative requirements for hydrogen storage devices to be accepted for use with fuel cells in these areas. Our goal is to provide an original analysis specifically addressing data missing in the literature.

This paper reports the opinions, perceptions, ideas, and suggestions of manufacturers, users, and technical experts in the both the military and consumer realms with whom the investigators engaged in conversation. In general, these parties intimately understand the needs of customers and strive to produce products that will meet those needs. Care is taken to not allow any technical biases that the researchers may have to intrude on the process. No judgments are made on the veracity of the feedback beyond investigators' judgment regarding whether or not the particular piece of feedback comes from a source "in the know" on a particular topic. The only modifications to this feedback occurred when it was ambiguous or conflicting, and in those instances the investigators attempted to resolve the ambiguities or conflict with the contributors involved or, failing that, used their own knowledge to clarify and decide the most appropriate technical requirements.

2. Method

The approach to this study was as follows:

1. Request feedback from stakeholders – those intimately involved with the design, manufacture, or usage of any fuel cell technologies – regarding various aspects of fuel cell device design, implementation, manufacture, and commercialization.
2. Identify categories of common portable electronics used today and compile major brand names and companies who produce each product, summarized in Table 1. To be as inclusive as possible, no assessment of the appropriateness of hydrogen fuel cells was made at this point.
3. Assess the status and potential of hydrogen fuel cells in these products by:
   a) Determining the benefits hydrogen fuel cells bring and the challenges they face in these products.
   b) Using active research, patents, news articles, and reports involving fuel cells in these products or by these companies as a gauge for where hydrogen fuel cells may be successful.
   c) Examining the markets for these products regardless of whether they currently use hydrogen fuel cells.
4. Select three specific applications for further investigation of the suitability for near-term hydrogen fuel cell deployment using the volume and extent of active research, the current value and volume of the market, feedback from manufacturers, and the existence of devices already containing fuel cell components.
5. Choose sample products in each application and identify their technical specifications and performance requirements.
6. Determine the requirements a hydrogen system (H_2 storage and fuel cell) would need in order to compete with the currently available portable energy storage technology in light of the feedback gathered.

3. Benefits and challenges assessment

This section contains the feedback received by engaging manufacturers of fuel cell and portable electronics devices. Several issues currently facing commercialized fuel cell systems are of interest when considering the potential for hydrogen-based power technology in different applications, and it is key to express what attitudes and perceptions exist in the market among stakeholders today. The feedback specifically regards portable power generators for military and consumer applications. However, some information is relevant to fuel cell devices in general.

3.1. *Size and weight*

The market perception is that fuel cell systems today are difficult to miniaturize. While there have been many

Table 1 – A list of products considered with brand names and companies.

Product category	Brand names/Companies considered
Broadband modems (mobile)	Sierra Wireless, Samsung, Novatel
Camcorders	GoPro, JVC, Flip Video, Insignia, Dynex, Sanyo
Cellular phones	Motorola, Apple, LG, Blackberry, HTC, Sony, Hitachi
Charging stations/power supplies	*Battery makers*: Duracell, Energizer, Maxwell, Panasonic, Rayovac, Sanyo, New Trent
	Fuel-cell related: mti micro (DMFC), myFC (sodium silicide), SFC Energy (methanol), Genport (H_2), Jadoo (metal hydride, H_2), UltraCell (methanol), Trulite, Samsung, Fuji Electric (propane, gas), Toshiba (methanol), Horizon (solid state)
	Gasoline-powered portable generators: All Power America, Briggs & Stratton, Eastern Tools & Equipment, Generac
	Honeywell, PowerMate
Digital cameras	Nikon, Canon, Casio, Fujifilm, Olympus, Kodak, Panasonic
DVD players (portable)	Philips, Toshiba, CyberPower, Golla
External hard drives	Iomega, LaCie, Seagate, Toshiba, Verbatim, Western Digital
GPS (handheld)	Garmin, Magellan, Bushnell, Sonocaddie
Headsets (telecomm.)	Belkin, Bose, Jawbone, Plantronics
Laptop computers	Compaq, Apple, HP, ASUS, Dell, Sony, Toshiba, Samsung
MP3 players	Apple, Zune, SanDisk, Creative, Archos
Radios (including 2-way)	Midland, Sirius, Pioneer, Sangean, Motorola, Uniden
Tablet PCs/iPads/E-readers	Amazon, Apple, Samsung, Barnes & Noble, Motorola
Video game systems (handheld)	Nintendo, Sony

developments in reducing the size of the fuel cell itself, the balance of plant for the total system (fuel cell + hydrogen storage) is a challenge [8]. There are extra size "costs" to the deployment of these systems: carrying electrical cables, fuel tubing, fuel cartridges, etc.

For the military, each of these issues ultimately affects the effective load carried by the soldier. With the goal of reducing the variety and quantity of batteries needed on the battlefield, the U.S. Army has identified the LI-145 battery as having the potential to reduce the soldiers' carried weight and to meet these targets [9]. This lithium ion battery provides benchmark gravimetric and volumetric energy densities to which current fuel cell technologies for portable power generation may be compared. These metrics may be used to develop the requirements for future hydrogen technologies. However, as mentioned below in the Infrastructure and Refueling section, if a fuel cell device is going to add an additional fuel logistics burden, it will not be good enough to just match the LI-145's size, but rather must be significantly smaller for the same stored energy to still make it attractive for deployment.

The form factor (shape) of the portable power device should also be conformal [10]. The U.S. military desires a device that can be easily and comfortably worn on the body, possibly tethered directly to the device to be recharged.

For consumer use, the size and weight requirements depend on the application. Specifically, for integration into a device such as a laptop computer or E-reader, the needed size and weight are very restrictive in order to meet the device's performance requirements.

3.2. *Device housing*

The U.S. military has specific requirements for devices to be used by its soldiers. Rather restrictive ruggedness requirements must be met; the products surveyed in this study were often stated to meet the standards of MIL-STD 810F or G. These requirements often add extra complexity to the overall fuel cell device [8], so the economic costs associated with meeting these stringent requirements is an issue. In one product examined, the small size requirements needed for military applications could only be met with an active cooling system requiring extra energy expenditure, whereas a simpler, passive system (without cooling fans nor energy use) would need to be larger [11].

3.3. *Fuel*

Feedback received from customers reveals uniform concerns about hydrogen fuel. The prevailing view is that major safety issues exist with hydrogen and with hydrogen supply infrastructure. This section describes these concerns in more detail.

3.3.1. *Safety*

Safety issues with using hydrogen compressed to high pressures were identified. The risk of stray bullets piercing the tank, for example, and other warzone hazards are of particular concern for wearing compressed hydrogen tanks in military applications. For this reason, the military is wary of any type of system requiring compressed gases or contents under high pressure [9]. As end users, the soldiers themselves must feel comfortable carrying and using such a system. The fuel must be safe, and perhaps more importantly, it must be *perceived* as safe.

Hydrogen storage systems based on metal hydrides, chemical hydrides and sorption materials all offer a path to lower stored hydrogen pressures and thus increased safety, although the reactivity of the material with air can be a concern if the storage tank were ruptured. However, metal hydrides are significantly heavier than alternative systems because a metal is used to bind and store hydrogen gas; their gravimetric energy densities are poor. Also, common chemical hydrides must be recharged off-board or have cartridges that are either disposable or recycled.

Device and fuel safety is a primary concern for the military, and given the dangerous environments that soldiers often face, a big problem for fuel cell systems is the potential hazards posed by the fuel. Some methanol fuel cell manufacturers have approached this issue by using methanol–water mixtures to reduce flammability risk while sacrificing energy density.

In non-combat applications, the threat of tank rupture is very small. Nonetheless, there is a perception of danger in compressed hydrogen storage. This concern may be alleviated somewhat through education and outreach that invite the public to experience hydrogen and fuel cells first-hand. For example, the public accepts widespread and informal use of gasoline, a highly flammable and toxic liquid, most likely due in large part to its century of use and familiarity.

3.3.2. *Infrastructure and refueling*

A major issue for both military and consumer hydrogen technology is the fuel supply. The infrastructure for hydrogen fuel is nowhere near as mature as that of gasoline or of the electrical grid, and for users away from the grid for extended periods, the availability of fuel is of paramount importance. For many consumers, hydrogen can be purchased in expensive, high-pressure tanks currently costing about $100/kg. The widespread availability of electricity, whether at military bases, workplaces, or homes, makes simply plugging a device into a wall outlet the preferred means of obtaining power. For example, the military would rather have a fuel cell unit with integrated electrolyzer that can be plugged into the base grid than use hydrogen to refill metal hydride canisters at in-country bases [12]. Most consumers would rather use the grid than use and replace a disposable fuel cartridge, let alone manually refill a liquid fuel like methanol (if available) [11]. For all users, inconvenience—or the perception of inconvenience—may deter interest.

Using fuels like methanol, propane, or hydrogen requires the creation of an energy supply chain and infrastructure whether for military or civilian consumers. For remote or hostile locations, there is a logistical challenge to supplying needed fuel. According to U.S. General David Petraeus' Operational Energy Memorandum released June 7, 2011, almost 80% of ground supply movement is of fuel [13]. A significant amount of resources is already required to secure such shipments, and many casualties have resulted from such activities. There is a desire to reduce the number of these resupply convoys, to increase energy efficiency, and to reduce energy expenditure. Feedback from the customer base indicates that a fuel cell system must offer a significant increase in energy density to warrant the creation of a new logistical system to transport a new fuel [9], assuming the infrastructure for the new fuel is feasible to begin with. The fuel type itself (e.g., hydrogen, methanol, propane) is not as important because there will be an additional logistical burden to supply the fuel regardless (unless it is the logistics fuel JP-8, which is used on the battlefield now). While a fuel cell's inherent higher efficiency will save some fuel, this advantage is considered too small by itself to be worth the additional resupply burden of a new fuel.

Furthermore, an important aspect of the fuel supply issue is the exact nature of the refueling process. The majority of currently available fuel cell generators use a cartridge mechanism for supplying fuel to the device, and such a system is an important consideration for developing a hydrogen infrastructure. A cartridge supply and recycle system may perhaps facilitate a greater shift toward hydrogen-based energy. By making the fuel supply in the consumer's eyes seem similar in nature to a typical battery, the refueling process is simplified, promoting consumer adjustment to and acceptance of the new technology.

An argument could be made that disposable batteries require replacement as well but are still widely used. The problem for fuel cells comes down to the availability of the fuel. With today's technology and infrastructure, neither hydrogen nor methanol can compare to the availability of simple batteries, and for low-power applications, there is no need to develop a new power system for fuel cells when batteries suffice. One piece of feedback the investigators consistently heard is that the fuel cell must not just meet the current technology's specification but must significantly exceed it if the fuel cell requires the user to take the additional step of refueling it.

3.4. *Energy requirements*

"Creeping featurism" is a phenomenon where devices continually gain more and more functions and features for end-user use, and it is a problem for consumer and military electronics designers in general [14]. The consequence of these added features is increased power consumption, causing the tendency for a commensurate growth in power demand. While this issue may be mitigated by effecting end-user changes in power consumption, it is nonetheless an issue when considering the overall energy and power requirements needed. This is particularly true for the military: overall carrying weight, and thus energy content, is becoming the factor limiting the technology used and is causing the U.S. Department of Defense (DOD) to decline additional capabilities that would otherwise be useful to the soldier [9].

3.5. *Power requirements*

The U.S. Army is interested in two different energy platforms for man-portable power: soldier-wearable power in the 20–50 W range and squad-level power of about 300 W [9]. To this end, field-testing of various energy solutions has been conducted by the 1–16th Infantry for Operation Enduring Freedom in Afghanistan. Several personal and squad-level power systems have been deployed there, including methanol fuel cell systems, solar power, and propane fuel cells, in addition to the traditional internal combustion engine (ICE) generators. Preliminary feedback indicated that very small ($\cong$20 W) individual power systems are not suited for direct use with radio equipment [10]. A spike of power around 80–85 W is needed during radio transmission, and the small 20 W methanol fuel cells used for this purpose were unable to provide that power – these fuel cell systems are current-limited and are meant to provide nearly constant levels of power. Such feedback indicates that these systems may be limited to constant power recharging applications unless integrated with another energy storage device such as a battery or capacitor.

Small, multipurpose fuel cell power generators in the 150–175 W nominal (300 W peak) range are being marketed for both military and civilian portable power applications. Their uses include medical life-support transport gurneys, portable radio relay stations for civilian services (police, fire, first responders, etc.), and indoor/outdoor power stations for consumers.

Consumer electronics such as cell phones require 5 W or less from a battery or recharger and are often limited to 2.5 W when using USB connectors. Laptop computers require more: on the order of 30–75 W.

3.6. *Product integration*

Integrating a fuel cell into a man-portable product (e.g., cell phone, PDA, laptop computer, etc.) is another challenge facing near-term application of fuel cells in consumer electronics that is the result of several issues. For example, there has been a push in the consumer electronics industry for closed-body designs—systems lacking open-air vents or ports [14]. This trend is disadvantageous for fuel cells, which require not only a fresh air supply but also a means of removing warm, humid waste air. This air-breathing characteristic of fuel cells would inhibit them from being integrated into any portable consumer electronics device that could be carried in a pocket or bag, such as a cell phone, tablet computer, or camera.

Air-exchange is not an issue for desktop computers because they already have active cooling systems necessitating an open-body design. However, even in laptops with open-body designs, adding an additional heat source to the system is highly undesirable [11]. Also, new developments in laptop cooling may render forced air systems obsolete, and thus the opportunity provided for fuel cells in open-body laptops may also disappear [14].

The pace of technological development in the personal portable electronics industry is also a concern, since the turnaround time for new devices is extremely swift. The speed at which new products are introduced into the market outstrips the current rate of fuel cell development, making it difficult for the fuel cell design to track the performance requirements of the application. In one example, by the time an integrated fuel cell prototype was developed for a laptop, the computer itself had already advanced three generations [8].

Improvements to both the energy efficiency of consumer electronics and the energy storage capacity of batteries both lead to smaller size for the integrated energy storage needed for a given run-time. As mentioned above, fuel cells already have trouble meeting these requirements, and industry contributors were quite pessimistic that fuel cell systems would ever be able to [12].

3.7. *Competition*

Feedback received from end users and manufacturers in the portable consumer electronics realm suggests that the large size of the consumer market does not necessarily lead to a greater opportunity for fuel cells. These devices face a large barrier of entry into the market because of competition with typical electrochemical cells. Batteries are the most common form of energy storage for portable consumer electronics, and with the rapid progress and constant development of battery technologies, it is unlikely that they will be displaced by another technology unless the new energy source can not only match the swift pace at which batteries are improving but also improve upon some aspect of the device, such as energy density or efficiency.

Most importantly, one piece of feedback has consistently resounded from those in the fuel cell industry, and it is especially relevant to consider the fact when looking at the future of hydrogen storage: with present technology, it is difficult for a fuel cell generator to compete with grid power. Energy from the grid is simply too inexpensive to compete with (it is considered free by most portable electronics consumers), and a typical consumer will always prefer a wall outlet over a portable power generator for normal consumer device recharging. The only realistic market perceived for fuel cell-powered devices is when this preference cannot be met: when grid power is not available for extended periods of time.

3.8. *End user interest and target audience*

In the military, man-portable fuel cell deployment can be bolstered if there is enough of a pull from the end user. Because it is the soldiers themselves who will be using these devices, their satisfaction or dissatisfaction with a device has a direct impact on the military's interest in pursuing such technologies and, consequently, on the usage and development of fuel cell devices for this market. As of 2011, none of the fuel cell sources of man-portable power were embraced by the soldiers evaluating them [9], although the potential of fuel cells is still attractive to the DOD.

While competing with grid power may be impractical for manufacturers of portable consumer electronics at the current state of fuel cell technology, there are opportunities in niche applications involving poor access to the grid. One of the advantages of fuel cell devices is precisely their independence from grid power. A typical consumer in conducting day-to-day activities is not always able to charge or power their electronic devices using wall outlets, and it is understood that fuel cells can facilitate a greater degree of freedom and portability. In other words, fuel cell generators could function as a substitutional good in relation to electricity from the grid. However, batteries would also be a substitute, and they already facilitate “energy independence” in almost all portable consumer electronics. As previously mentioned, because of the rapid progress in battery technology, it is difficult for fuel cells to compete in such an application.

It is in applications requiring energy beyond what is available in batteries that fuel cells may find much more use, but this market segment is a small subset of the total consumer electronics market audience. In the man-portable consumer electronics market, very few customers are away from grid power sources for weeks at a time, and most people have access to grid power at least once a day.

Despite this, fuel cells may have significant near-term potential for both integrated portable device power and portable rechargers with the following categories of users [11]:

1. Campers and other sportsmen who are away from the electric grid for extended periods of time.

2. "Power users" of laptops and other personal electronic devices who have a high demand for energy.
3. Consumers who are interested in reducing the environmental impact of computers, because fuel cells potentially create less pollution than devices powered from the grid.
4. Professionals working remotely, such as border patrol, emergency medical personnel, and troubleshooting and repair personnel.
5. Markets where there is unreliable electric grid power or none at all.

4. Market assessment

Of the 14 product categories examined (Table 1), only four indicated active or past fuel cell research as shown in the open literature from patent filings and news articles. These four categories are: (1) cellular phones, (2) charging stations and power supplies, (3) digital cameras (specifically d-SLRs, or digital single lens reflex), and (4) laptop computers. The lack of industry pursuit of fuel cell technology in the other ten product categories is taken as a strong indicator that the companies in these industries do not believe hydrogen fuel cells can be commercially successful.

Of these four consumer electronics categories, fuel cell systems are only commercially available in category 2: portable recharging devices and power supplies. Their potential application as portable, off-grid power supplies is appealing to both consumers and the military. Portable fuel cell generators have many applications for military use, and because the U.S. military has very specific form factor and ruggedness standards and requirements, military systems constitute their own category. All other end users would fall into the consumer category, where environmental and other requirements are typically more relaxed than those of the military. The current availability of these systems, their potential for future deployment, and end user interest in portable power generation indicate that portable power applications are an important application for fuel cells and require further analysis.

For the military, estimates of the U.S. Army market were made based on feedback that considered the number of platoons with the potential to operate on remote missions [9]. It was found that approximately 2100 fuel cell units of 300 W size would be enough to meet this demand, assuming two 300 W units per applicable platoon used to charge the entire platoon's batteries. In the case of smaller, personal fuel cells that each soldier could use to power their equipment, if it is assumed that each applicable platoon has 38 soldiers, approximately 40,000 units would be needed to meet this need.

Additional information is needed to select which of the other groups are the most viable for fuel cell deployment in the near-term. Market data is a useful criterion for prioritization, and Figs. 1 and 2 show 2009 market value and volume data for both the United States and global markets. The market value and volume for d-SLR cameras are a small minority of the total digital camera market. Cellular phones have an immense market volume globally, although their dominance in the U.S. is not as pronounced, and they have the least market value. To give perspective, consumer electronics, which consists of audio visual equipment and video game consoles among others, have the greatest market value compared to both personal computers and cellular phones.

Mobile computers (which compose 54.3% of the global PC market and include laptops, notebooks, netbooks, and tablet PCs) have a substantial market share in portable consumer electronics as a whole. They hold an intermediate position in terms of both value and volume, and from 2009 to 2014 the global PC market is expect to grow + 8.6% in value and + 62.9% in volume (−7.4% in value and + 43% in volume for the U.S. market).

In spite of the fact that future laptop computers might evolve into a closed body design, thereby precluding fuel cell use in the future, most laptops currently have open-enclosure architectures, so there is interest in the development of fuel cell systems for them. Laptops generally have a large energy and power requirement and are big enough volumetrically to support a fuel cell system at today's level of technology and miniaturization. In contrast, the size of today's cellular phones and their closed-body designs are restrictive factors for fuel cell integration. Although companies like Angstrom Power (Vancouver, Canada) have created prototype cellular phones with integrated fuel cells, there seems to be more interest in portable computing because of fuel and integration considerations. Given the interest in laptop computers within the fuel cell industry along with the market's vitality, laptops were selected for further analysis, whereas cell phones were not.

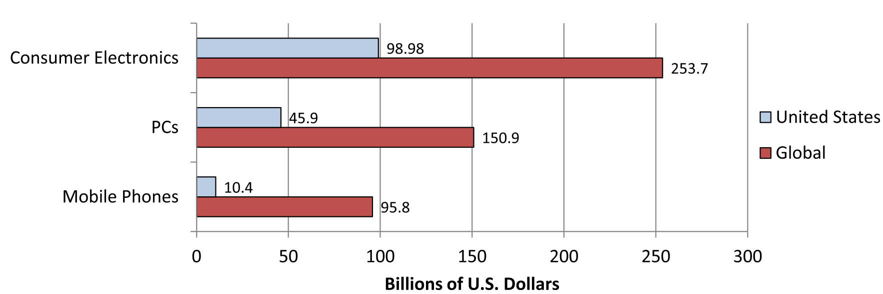

Fig. 1 – Market value (billions of U.S. dollars) of consumer electronics, PCs, and mobile phones for 2009. Laptop computers are about 54% of the total PC market. "Consumer Electronics" includes audio visual equipment (CD players, DVD players and recorders, hi-fi systems, home theater, in-car entertainment systems, portable digital audio, radios, televisions, and video recorders) and video game consoles (home and portable). Data from Datamonitor [15–20].

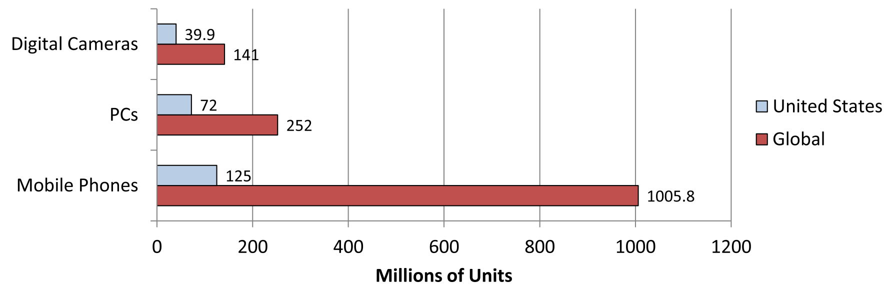

Fig. 2 – Market volume (millions of units sold) of digital cameras, PCs, and mobile phones for 2009. Digital SLR (d-SLR) cameras are a small portion of all digital cameras. Data from Datamonitor [15–18], digital camera data from Tarr [21].

5. Selected applications and technical specifications

Considering the preceding sections, both military and consumer portable rechargers and power generators are chosen as the most attractive target for near-term introduction of fuel cell technology because of their current availability and deployment and their veritable market potential. Because of the differences in requirements, these devices are separated by virtue of their two audiences. The third category is laptop computers because of fuel and size requirements and existing R&D of integrated fuel cell systems. While some research has been conducted in cell phones and d-SLR cameras, their size and design reduce their potential for realistic near-term deployment.

5.1. *Rechargers and power supplies*

Because small fuel cells themselves are power sources, it is not surprising that their application as independent power generators is the most prominent in the market today. These fuel cell generators face perhaps the smallest barrier to entry into the market because they are not reinventing or even replacing conventional energy storage technologies, such as batteries. In fact, they work in concert with the existing energy storage in typical consumer electronics by inherently relying on the device's batteries or other power source and are made for recharging purposes. In this way, instead of competing with batteries—a highly developed and well-established multi-billion dollar industry—fuel cell rechargers utilize them by coupling fuel cell-based power generation with the energy storage capacities in existing batteries. Furthermore, from an economic point of view, the cost of such fuel cell systems is effectively distributed over all of the devices recharged, making an external, rather than integrated, fuel cell device more appealing to manufacture and to use [22].

Many current fuel cell technologies used for mobile rechargers and power supplies rely on methanol. The simplest alcohol, methanol is a liquid at ambient conditions, dense in energy, and relatively stable. In direct methanol fuel cells (DMFCs), methanol is fed into the fuel cell stack, and carbon dioxide and water are released as waste products. Methanol is also used in the reformed methanol fuel cell (RMFC), such as that developed at the Lawrence Livermore National Laboratory [23]. This technology reforms the methanol into hydrogen gas and carbon dioxide before being fed into a so-called "high-temperature proton exchange membrane (PEM)" fuel cell. Because of the carbon in the alcohol, a methanol system can be carbon neutral only if the methanol is produced renewably. However, methanol is popular because of the relative ease with which the fuel can be handled and stored, as compared to hydrogen. From an environmental standpoint, there is much opportunity for a hydrogen fuel cell to compete with methanol fuel cells because hydrogen gas is a carbon-free energy carrier.

5.1.1. *Military*

The modern soldier's repertoire of equipment has significantly increased overall energy demand. The storage devices needed to provide sufficient energy for individual power consumption have led to an overall increase in the weight of each soldier's load. The weight that an individual must carry has been correlated with an increased incidence of musculoskeletal injury [9], so an effort is being made to find lightweight technologies capable of providing the requisite amount of energy and power. Furthermore, an energy solution must not only have a size that is portable, but also a form factor that does not hinder a soldier's maneuverability.

Batteries are currently employed by the military to satisfy man-portable energy demand. Both primary (single-use) and secondary (rechargeable) batteries are used in the field. In the U.S. Army, soldiers typically carry a variety of primary batteries for each piece of equipment, and for those devices with secondary batteries, they carry another battery to recharge the device batteries. In this way, the versatility of the power source is necessary. For reference, a U.S. Army rifle platoon (usually 38 soldiers) requires approximately 155 lb (70 kg) of batteries for a 24 h mission (2012 projection), and 412–436 lb (187–198 kg) for a 72 h mission (2010 data) [9]. Different personnel carry different amounts of batteries depending upon their duties, but this works out to an average per soldier of 4 lb (2 kg) for a 24 h mission and 11–12 lb (4.9–5.2 kg) for a 72 h mission.

The ultimate goal for the U.S. Army is to have personal power supplies for each soldier on mission acting as continuous "battery toppers" or even to power their devices directly. This need could be met by a fuel cell in the 20–50 W power range for each solider. Of interim interest are 300 W systems because these larger systems have less restrictive requirements. At the platoon level, two of these systems can provide

the needed recharging power for all the platoon's batteries when the platoon is at rest.

The lithium-ion battery LI-145 is presented as a benchmark against which any new technology would need to compete with. This is the "workhorse" battery for the U.S. Army's remote deployments. Its specifications are given in Table 2. Using its energy density, one can see how currently available portable power systems compare. Figs. 3 and 4 plot gravimetric and volumetric energy densities respectively, for the entire system (storage and power generating device) from the specifications of portable generators marketed for both military and consumer use. The chart organizes the systems according to fuel source. The horizontal line on the charts is the energy density of the LI-145 battery. The charts show that fuel cell systems perform well on a gravimetric basis, with 8 of the 15 sample fuel cell systems exceeding the gravimetric energy density of the LI-145. However, only 3 of the fuel cell systems have a better volumetric energy density. All of the fuel cell systems that meet or exceed the LI-145 benchmarks are methanol-powered. It is also evident from Fig. 3 that there is a trend for the larger-mass systems to have a higher gravimetric energy density: the higher mass of these systems is due to more fuel being carried while the fuel cell remains constant. This trend is not observed for volumetric energy density (Fig. 4).

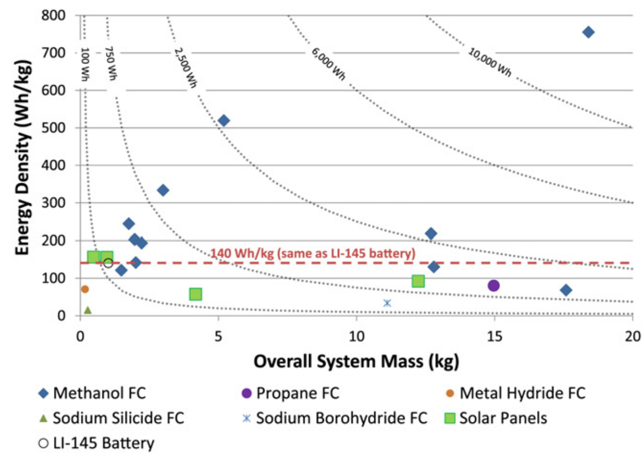

Fig. 3 – Gravimetric energy density of various currently available portable power systems. Data are for entire systems (power generating device, fuel storage, and full fuel). Solar panel data assumes access to sunlight for 5 h and 75% electrical system efficiency. The curved dotted lines are constant energy curves and denote total stored energy. The dashed horizontal line indicates the LI-145 energy density (140 Wh/kg) as a reference.

Table 2 – Specifications of the LI-145 military personnel battery from UltraLife. The stated specifications for the LI-145 supplied by Bren-Tronics are identical.

Specification	Military personnel battery
Manufacturer	UltraLife, Bren-Tronics
Model	LI-145
Rated output power	28.6 W
Run duration per fill/charge	5 h max, 1 h @ rated power and 80% depth of discharge
Output power type	10.0–16.8 VDC (15.2 VDC nominal)
Overall dimensions – $L \times W \times H$	21.0 cm × 4.22 cm × 7.4 cm
Overall volume	651 cm^3
Overall dry (no fuel) weight	1.02 kg (2.2 lb)
Fuel/battery type	Lithium ion
Fuel tank or charge capacity	9.4 A h
Stored energy (kWh)	143 Wh
Energy storage system volume	0.65 L
Energy storage system volumetric energy density	220 Wh/L
Energy storage system weight	1020 g
Energy storage system gravimetric energy density	140 Wh/kg
Engine/FC model	Not applicable
Power system (Engine/FC) weight	Not applicable
Power system (Engine/FC) volume	Not applicable
Combined energy + power system volume	651 cm^3
Combined energy + power system volumetric energy density	220 Wh/L
Combined energy + power system weight	1.02 kg (2.2 lbs)
Combined energy + power system gravimetric energy density	140 Wh/kg
Refuel/recharge time	2.5–3 h from empty at C/2
Fuel consumption	Not applicable
Emissions	None
Operating temperature range	−32 °C to 55 °C
Noise level	Not available
Overall cost	Not available

Energy storage system refers to the full fuel tank and/or batteries with associated hardware.

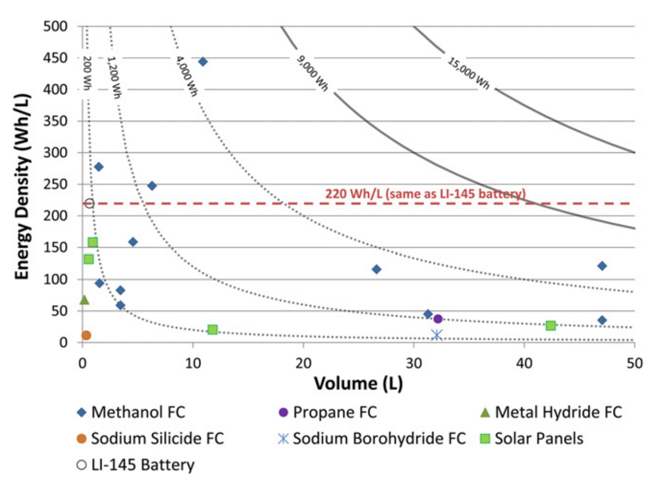

Fig. 4 – Volumetric energy density of various currently available portable power systems. Data are for entire systems (power generating device, fuel storage, and full fuel). Solar panel data assumes access to sunlight for 5 h and 75% electrical system efficiency. The curved dotted lines are constant energy curves and denote total stored energy. The dashed horizontal line indicates the LI-145 energy density (220 Wh/L) as a reference.

To reiterate, for military portable power needs, a hydrogen system must at least exceed the gravimetric and volumetric energy densities of the Li-145 lithium battery. It must meet military standards for ruggedness and be in a conformal shape for possible on-body use. It must also exceed the minimum safety requirement to be welcomed for use by soldiers. The fuel must impose minimal strain on the military's logistical operations or perhaps utilize the existing energy infrastructure of a country or region. Compressed gas does not look favorable because of the risk of explosion. Metal hydrides (such as $LaNi_5H_6$ and $NaAlH_4$) look promising but must overcome relatively poor gravimetric energy densities. Chemical hydrides (such as NH_3BH_3) are also another area with potential.

There has been some research toward certain metal hydride hydrogen storage in which the decomposition reaction that liberates hydrogen gas requires energy. Alane (AlH_3) is one such hydride whose decomposition is endothermic [11]. This type of hydrogen storage may be of particular interest to address the heat rejection issue and various safety issues regarding thermal runaway, but ultimately keeping the temperature below an acceptable level will be an issue for any electronic device that has an integrated fuel cell system.

As for the current hydrogen technology being used in the military for portable power, nothing has been considered by the U.S. Army for demonstration or deployment because no companies have submitted a device for evaluation, even at Technology Readiness Levels (TRL) 4, 5, or 6 [9] – a metric used by the military to measure readiness of a technology for deployment.

Table 3 gives the specifications of available fuel cell technologies (all methanol-based) for a military battery charger that a hydrogen-based system would need to compete with. The exact specification for a viable hydrogen technology depends on the application; the U.S. Army is flexible to a certain degree regarding device specifications and is willing to sacrifice some specifications for large increases in energy density (gravimetric and volumetric). The most important attributes a system must have are that it is proven safe and easily produced in large quantities. User requirements are also highly dependent on application [9].

5.1.2. *Consumer*

The landscape of the consumer market for portable fuel cell products is considerably different from that of the military market. The current target for portable recharging is small devices with USB connectivity, with emphasis on rechargers for cellular phones and other portable electronics – see Table 4 for current and past products. The fuel cells themselves are compact and versatile. For example, each of the existing systems is small enough to be carried in-hand and relatively lightweight, producing 5 W of power. Replaceable fuel cartridges are the most common way to refuel these small fuel cells, but there are systems where fuel must be poured into the device. Fuel supplied via cartridges is also sold in addition to the system, but the bulk of the initial cost is in the system and not the fuel.

Competing energy sources (e.g., grid power, batteries) pose an immense obstacle in the way of more widespread adoption of small fuel cell technologies in the consumer electronics arena. One potential advantage of a fuel cell power source—a longer device operating time—is perhaps less important to a typical consumer, who will only rarely be away from grid power sources for an extended time period. A viable hydrogen fuel cell and accompanying hydrogen storage must be conscious of the target consumer audience for its products. While there are less explicit requirements for the system's performance, issues like efficiency, weight, size, power rating, and energy content indirectly influence the subset of consumers who would be interested in such a technology. A competitive system that is easy to use, extremely portable, and environmentally friendly could perhaps appeal to a larger group of consumers.

According to the market feedback received, in competition with any kind of fuel cell system are the battery-based, grid-powered recharger systems on the market. These enable a user to be away from the grid for an extended period of time and have impressive performance, price, and size. Because of the inconvenience of fuel cell refueling (including obtaining the hydrogen and refilling/replacing the storage vessel) compared to the ease of grid-recharging, fuel cells would have to not just meet but significantly exceed the capabilities of these devices in order to compete. For example, one company surveyed offered that to overcome this inconvenience, a portable fuel cell device would need a runtime of more than ten-times that of an otherwise-identical grid-rechargeable device [14]. In other words, they feel a consumer would accept the effort of refueling if they only had to do it one-tenth as often. While this is just one example and may not be applicable to all devices, it highlights consumers' extreme sensitivity to any possible device inconvenience; in this case the act of plugging something into a wall outlet versus that of finding, purchasing, installing, and refilling some kind of fuel.

The current specifications of portable commercialized battery and fuel cell recharger systems are presented in Table 4. The data in the table below indicate that battery-based systems currently have 2–5 times the energy density as fuel cell based systems; it will be a challenge for similarly sized fuel cells systems with comparable amounts of stored energy to catch up, much less achieve 10 times *greater* energy density than the battery systems shown. An example of this phenomenon can be seen in Fig. 5, which compares the mass of the LI-145 battery to that of a methanol fuel cell system (fuel cell and fuel). It can be seen from the figure that as the amount of required stored energy is increased, the fuel cell system becomes the lower-mass option.

It is inherently more difficult for fuel cells to compete with batteries on an energy density basis when the amount of stored energy is small. A comparison of the gravimetric energy density of commercially-available reformed methanol fuel cell (RMFC) systems with available Li-ion batteries, both marketed for military use, is shown in Fig. 5. By comparing the fuel cell system data (triangles and diamonds) to the battery data (squares) when the amount of stored energy is near zero, it can be seen the fuel cell systems have a larger mass than the battery system. This is because the mass of the fuel cell and its accessories is more than that of the battery casing and its accessories. These data points also illustrate that higher-power fuel cells (the diamonds, 50 W nominal) have more mass than lower-power fuel cells (the triangles, 25 W nominal). Thus, at high powers and low stored energy, the battery is the preferred solution.

Table 3 – Summary table of existing man-portable fuel cell-powered battery chargers for the U.S. military. All are powered by methanol; at a minimum, a hydrogen-powered fuel cell would have to meet these specifications to compete in the market.

Specification	Manufacturer		
	SFC energy	UltraCell	Protonex
Model	JENNY 600S	XX55	M300-CX
Rated output power	25 W	50 W	300 W
Run duration per fill/charge	11.4 h (60% methanol/40% water) or 16 h (100% methanol) @ rated power	10 h @ rated power, 21 h @ 40% load	4.4 h @ rated power
Output power type	10–30 VDC	12–33 VDC	28 VDC nominal
Overall dimensions – $L \times W \times H$	25.2 cm × 18.4 cm × 7.44 cm	27.2 cm × 20.8 cm × 8.1 cm	30 cm × 37 cm × 24 cm
Overall volume	3.45 L	4.58 L	26.6 L
Overall dry (no fuel) weight	1.6 kg	1.6 kg	16 kg
Fuel/battery type	Methanol	Methanol	Methanol
Fuel tank or charge capacity	350 mL	550 mL	2 L
Stored energy (kWh)	400 Wh (100% methanol), 285 Wh (60% methanol/40% water)	430 Wh	1200 Wh
Energy storage system volume	0.385 L (est.)	1.146 L	2.2 L (est.)
Energy storage system volumetric energy density	1143 Wh/L (100% methanol)	375 Wh/L	545 Wh/L
Energy storage system weight	371 g (regular) 410 g (desert)	620 g	1588 g
Energy storage system gravimetric energy density	1078 Wh/kg (100% methanol)	694 Wh/kg	756 Wh/L
Engine/FC model	PEM	PEM	SOFC
Power system (Engine/FC) weight	1.23 kg (est.)	1.6 kg (est.)	16 kg
Power system (Engine/FC) volume	3.065 L (est.)	4.58 L (est.)	26.6 L
Combined energy + power system volume	3.45 L	5.73 L	28.8 L
Combined energy + power system volumetric energy density	116 Wh/L	75 Wh/L	41.7 Wh/L
Combined energy + power system weight	1.971 kg	2.22 kg	17.6 kg
Combined energy + power system gravimetric energy density	203 Wh/kg	193.7 Wh/kg	68.2 Wh/kg
Refuel/recharge time	<5 min (est.)	<5 min (est.)	<5 min (est.)
Fuel consumption	<1 L/kWh @ 25 W	Not available	450 mL/h @ 100% load
Emissions	CO_2, water	CO_2, water	CO_2, water
Operating temperature range	−32 °C to 35 °C (Reg), 10 °C–55 °C (Desert)	−20 °C to +50 °C	−20 °C to +50 °C
Noise level	< 37 dB @ 1 m	Not available	Not available
Overall cost	Not available	Not available	Not available

Energy storage system refers to the full fuel tank and/or batteries with associated hardware.

However, when the amount of stored energy is increased, the fuel cell becomes favorable over the battery, and its advantage increases as more and more energy storage is required, as long as the nominal power requirement remains constant. This is because the gravimetric energy storage densities of common fuel cell fuels (methanol in this example) are inherently greater than that of the chemicals used to store energy in batteries. Thus, fuel cells are the preferred solution at low powers and high amounts of stored energy.

5.2. *Laptop computer power*

Unlike portable power generators, there are no commercially available laptop computers with integrated fuel cell systems. The lack of integration into consumer electronics reflects the current state of fuel cell development and of the impediments that block fuel cell deployment. While large electronics and computer companies have been filing a significant number of patents for fuel cell-related technology, the existence of these patents suggests that at most, companies are doing research and have taken action to protect their inventions. Whether or not the subject of the patent will ultimately lead to a commercial product is unknown.

Because remote users are expected to be attracted to an integrated fuel cell system, this study specifically focused on ruggedized laptops designed specifically for this market segment. For example, Panasonic has explored the possibility of fuel cell integration with its own laptops [8]. The commercialization of such laptops indicates that the market does

Table 4 – Specifications for portable consumer rechargers, both battery and fuel cell-based.

Specification	Type				
	Battery	Battery	Fuel cell	Fuel cell	Fuel cell
Manufacturer	New Trent	Energizer	myFC	Horizon Fuel Cell Technologies	Toshiba America Electronic Components
Model	iCruiser IMP1000	XP4001 Travel Charger	PowerTrekk	MiniPAK	Dynario
Rated output power	2.5 W	2.5 W	2.5 W	2.5 W	2.5 W
Run duration per fill/charge	13.2 h @ rated power and 60% DOD	4.8 h @ rated power and 60% DOD	3.9 h @ rated power and 60% DOD battery	4.8 h @ rated power	4.8 h @ rated power
Output power type	5 VDC	5 VDC	5 VDC	5 VDC	5 VDC
Overall Dimensions – $L \times W \times H$	$10.2 \times 9.5 \times 2.9$ (cm^3)	$13 \times 8 \times 1.4$ (cm^3)	$6.6 \times 12.8 \times 4.2$ (cm^3)	$10.4 \times 6.8 \times 2.5$ (cm^3)	$15.0 \times 2.10 \times 7.45$ (cm^3)
Overall volume	281 cm^3	146 cm^3	355 cm^3	177 cm^3	235 cm^3
Overall dry (no fuel) weight	285 g	150 g	200 g (no battery)	80 g	280 g
Fuel/battery type	Lithium polymer battery	Lithium polymer battery	Hybrid: Fuel cell + NaSi powder and Li-ion battery	Fuel cell + metal hydride H_2	Hybrid: Direct methanol fuel cell and Li-ion battery
Fuel tank or charge capacity	11,000 mAh	4000 mAh	2600 mAh (1600 mAh in battery, 1000 mAh in fuel)	2400 mAh	2600 mAh (estimate) (660 mAh in battery)
Stored energy (kWh)	55 Wh	20 Wh	9.9 Wh (4 Wh in fuel, 5.9 Wh in battery)	12 Wh	13 Wh (estimate)
Energy storage system volume	0.28 L	0.15 L	0.195 L (est.)	0.031 L	0.022 L
Energy storage system volumetric energy density	196 Wh/L	137 Wh/L	50.8 Wh/L	390 Wh/L	591 Wh/L
Energy storage system weight	285 g	150 g	150 g (est.)	75 g	31 g
Energy storage system gravimetric energy density	193 Wh/kg	133 Wh/kg	66 Wh/kg	160 Wh/kg	419 Wh/kg
Engine/FC model	Not applicable	Not applicable	PEM	PEM	DMFC
Power system (Engine/FC) weight	Not applicable	Not applicable	135 g (est.)	80 g	260 g
Power system (Engine/FC) volume	Not applicable	Not applicable	0.159 L (est.)	0.146 L (est.)	0.213 L
Combined energy + power system volume	281 cm^3	146 cm^3	0.355 L	0.177 L	0.235 L
Combined energy + power system volumetric energy density	196 Wh/L	137 Wh/L	28 Wh/L	68 Wh/L	55 Wh/L
Combined energy + power system weight	285 g	150 g	285 g	155 g	291 g
Combined energy + power system gravimetric energy density	193 Wh/kg	133 Wh/kg	34.7 Wh/kg	77 Wh/kg	45 Wh/kg
Refuel/recharge time	4–5 h (user feedback)	4 h	Cartridge swap	Cartridge swap	<1 min
Fuel consumption	Not applicable	Not applicable	Not available	Not available	Not available
Emissions	None	None	Water	Water	Water and CO_2
Operating temperature range	−10 °C to 45 °C	n/a	5 °C–30 °C	0 °C–40 °C	10 °C–35 °C
Noise level	No noise	No noise	Not available	Not available	Not available
Overall cost	$76.95 (as of 9/12/2011)	$49.99 (as of 9/12/2011)	$200 + $2 for each fuel cartridge (forecast)	$99 with 2 cartridges, $9.99 per cartridge. Higher production levels[a]: $29.99 for unit and $5.99 for cartridge	$325 (reported 10/29/2010, since discontinued)

Energy storage system refers to the full fuel tank and/or batteries with associated hardware.
a The number of units corresponding to “higher production levels” has not been publicly defined by the manufacturer.

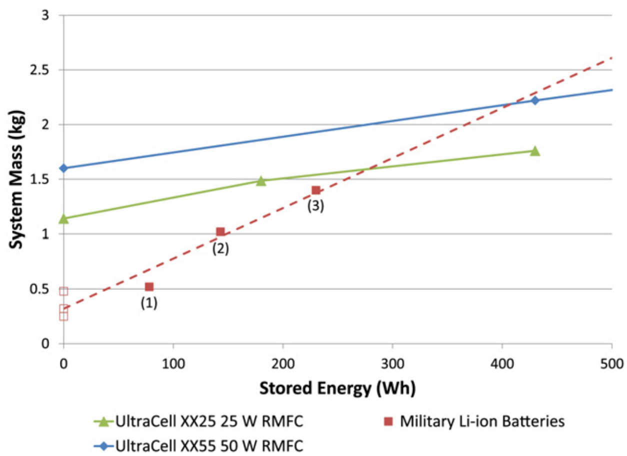

Fig. 5 – A comparison of the mass of sub-100 W fuel cell and battery energy systems marketed for military use. The filled points are manufacturers' data. The numbered points are different batteries: (1) LI-80 (17 W @ rated capacity to 76 W max continuous); (2) LI-145 (29 W @ rated capacity to 76 W max continuous); (3) BB-2590 (12 W @ rated capacity to 133 W max continuous). The open squares on the vertical axis are the masses of (1), (2), and (3) less the mass of 6, 12, and 24 18650 Li-ion cells, respectively, i.e., the calculated "zero stored energy" masses. The dashed line is a linear fit to the battery data. At low required amounts of stored energy, the battery is the lowest mass solution, while at higher amounts of stored energy the fuel cell is preferred.

indeed exist, giving hope for future development of integrated fuel cells.

An integrated laptop system must have very sensitive temperature and perhaps a humidity controls to deal with the fuel cell waste heat. As with portable power, a hydrogen fuel cell option must be able to, as a system, meet or exceed the performance of laptop computer batteries. A storage solution that acts as a heat sink would be extremely beneficial in the overall system design. The device and fuel storage must also be rugged enough for normal operation.

Panasonic's Toughbook (battery-powered) series is a prime example of the ruggedized laptop computer that would be of interest to the remote user. Panasonic offers models with different degrees of ruggedness. The fully ruggedized model with the longest battery life model was selected for illustration, the Toughbook 31 (specifications given in Table 5).

Table 5 – Specifications of the Panasonic Toughbook 31 laptop computer.

Specification	Laptop computer
Manufacturer	Panasonic
Model	Toughbook 31 (i5 CPU)
Rated output power	8 W (idle) to 35 W (heavy use)
Run duration per fill/charge	12.5 h at idle, 2.6 h at heavy use
Output power type	10.65 VDC (battery)
Overall dimensions – $L \times W \times H$	11.5″ × 11.9″ × 2.9″
Overall volume	6.51 L
Overall dry (no fuel) weight	3.6 kg
Fuel/battery type	Li-ion
Fuel tank or charge capacity	8.55 A h
Stored energy (kWh)	91.1 Wh
Energy storage system volume	0.774 L
Energy storage system volumetric energy density	118 Wh/L
Energy storage system weight	475 g
Energy storage system gravimetric energy density	192 Wh/kg
Engine/FC model	Not applicable
Power system (Engine/FC) weight	Not applicable
Power system (Engine/FC) volume	Not applicable
Combined energy + power system volume	0.774 L
Combined energy + power system volumetric energy density	118 Wh/L
Combined energy + power system weight	475 g
Combined energy + power system gravimetric energy density	192 Wh/kg
Refuel/recharge time	3.5–4 h
Fuel consumption	Not applicable
Emissions	None
Operating temperature range	5 °C–35 °C
Noise level	Not available
Overall cost	$4000 for the computer, $160 for the battery (reported 12/12/11)

Energy storage system refers to the full fuel tank and/or batteries with associated hardware.

6. Hydrogen storage requirements

A variety of issues face hydrogen storage and hydrogen fuel cell deployment in the portable electronics industry. As an energy source, perhaps the most relevant metrics of fuel cell performance are its gravimetric and volumetric energy densities, and because the properties of the fuel are directly related to the total energy density of a system, storage is of primary concern when assessing the future of fuel cell technology. Methanol systems currently dominate this market segment because of the fuel's relatively high energy density, ease of storage, and superior safety issues.

To compete, a hydrogen system must at least achieve energy densities comparable to methanol systems. Significant increases in energy density are important for hydrogen storage development, but many other factors must be dealt with for widespread, near-term deployment of hydrogen fuel cells in man-portable electronics. Issues of safety, compactness, fuel infrastructure, energy competition, market expanse, refueling method, and public perception all affect the viability of the technology in this man-portable consumer electronics realm.

For the military, the higher efficiencies that fuel cells may offer over other energy sources may appear to be attractive. But from a macroeconomic level, the device must offer some strategic advantage in terms of weight or volume to be worth

deployment. Thus, while fuel cell efficiency may realize some savings, this alone is not big enough of a push for widespread, near-term deployment [9].

The inability of a practical fuel cell system to match the small size of batteries integrated into handheld consumer electronics along with its air-breathing behavior prevent them from being integrated into nearly all of these devices. Where larger sizes and air-breathing are not issues, the fuel cell and hydrogen storage system must either:

1. Be as convenient as a battery-grid system, or
2. Have such a large increase in "performance" (defined by the user) as to make its inconvenience a secondary issue.

In the first case, the availability of hydrogen is the primary obstacle to convenience. When hydrogen is available, it is usually accompanied by complex and/or unfamiliar equipment that is daunting for the average user. Until this issue is solved, the early market approach needs to essentially insulate the user from hydrogen. This is done by introducing cartridge-type systems that consumers can buy at their local stores and either recycle (similar to the propane exchange at many stores and preferred by manufacturers) or throw away (preferred by most consumers for its convenience, whether civilian or military). This is one of the reasons that chemical hydrides, and to a lesser extent metal hydrides, are currently the preferred hydrogen storage technology for fuel cells geared to portable power and consumer electronics.

In the second case, if "obvious" hydrogen storage methods are to be used (i.e., compressed gas, liquid, user-refillable metal hydrides, etc.), the inconvenience must be counterbalanced by significantly improved performance. In the military example, a three-fold increase in energy density of the entire system over the best battery technology is required to make up for the extra refueling burden [9], whereas in the consumer electronics realm, a more than ten-fold increase was required in one case, highlighting the extreme sensitivity that consumers have toward any inconvenience in a product.

As a summary, Table 6 lists the determined requirements for a man-portable hydrogen fuel cell system that could fulfill the same function and still be acceptable to the end user. Table 6 is the result of feedback on what users and manufacturers require from their equipment, which has been described in detail in the preceding sections. In several cases, the feedback was unanimous in stating that the requirements for a hydrogen fuel cell-powered version of a piece of equipment to match the specifications of the existing equipment, so in those instances the numbers used for the requirements are generated largely from the specifications (shown previously in Tables 2–5). In cases where the feedback indicated differences between what they would like to see in fuel cell versions and the current equipment, the numbers received through feedback are used to generate the requirements shown in the table.

Table 6 – Energy storage requirements for a hydrogen fuel cell powered version of each man-portable power supply and consumer electronics device.

Application	Military personnel battery	Consumer battery charger	Specialized laptop computer
Rated output power	30 W nominal and 85 W for short bursts	2.5 W	8 W (idle) to 35 W (heavy use)
Run duration per fill/charge	> 15 h	40 h–100 h @ rated power	8 h–24 h at heavy use
Energy storage system volume[a]	0.65 L	0.28 L	0.774 L
Energy storage system weight[a]	1.02 kg	0.285 kg	0.475 kg
Refuel/recharge time	Cartridge swap	Cartridge swap	Cartridge swap
Operating conditions – temperature	MIL-STD-810 (−31 °C to 49 °C)	−10 °C to 45 °C	MIL-STD-810 (−31 °C to 49 °C)
Operating conditions – weather[b]	Extreme (MIL-STD-810)	Not designed for weather exposure	MIL-STD-810, IP65 enclosure
Noise level[c]	Negligible	Negligible	Negligible
Emissions	Warm air or none	Warm air or none	Warm air or none

a Energy storage system refers to the full fuel tank and/or batteries with associated hardware. Restrictions on size assume the storage of enough energy to meet the rated output power for the required run duration; if more energy is stored these restrictions may be relaxed.
b Extreme weather conditions include rain, snow, hail, ice, blowing sand, blowing water, dirt, mud, dust, high elevation, salt air, and humidity extremes.
c When operating at rated load, at a distance of 5 m.

7. Conclusions

Three potential near-term applications for hydrogen fuel cells were identified in the man-portable power and consumer electronics market: (1) power supplies for the military, (2) power supplies for the consumer, and (3) laptop computers. In the military power market, current portable fuel cell solutions focus on battery chargers, but since the U.S. military's ultimate goal is a battery replacement, that application is selected here. For consumer power, the portable hydrogen fuel cell product that is most likely to be accepted by the end user in the near term is a battery charger with cartridge refueling. In either application, the end users conveyed that the advantage of a hydrogen fuel cell is either the ability to replace grid power when unavailable or the replacement of fossil-fuel generators with a quieter and convenient zero-emissions solution. The laptop computer market was identified as being the only potentially feasible niche for a fuel cell to be integrated into a portable product in the near term. The primary benefit is seen to be longer run times, but competition with currently used batteries is problematic.

Those in consumer electronics feel strongly that a device that requires the consumer to manually refuel it with hydrogen, in its current state of availability, will not be sufficiently successful in the marketplace to justify developing such a product, even though there may be no other barriers to

commercialization. The portable power and consumer electronics market has further concerns about the air-breathing behavior of fuel cells that preclude them from inclusion in many devices, the additional heat generation, and the size to compete with batteries for all but specialized applications. Improvements in energy density, fuel availability, and public perception are all needed for near-term hydrogen fuel cell deployment in man-portable electronics.

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